Multi agent electric vehicle control based primary frequency support for future smart micro-grid

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Abstract: *A high penetration level of renewable energy sources such as wind power turbines and solar photovoltaic generation, in micro-grid systems causes some problems to micro-grid operator, e.g., lack in primary reserve. Recently, many countries around the world decided to increase their electric vehicles in the near future which provide a good chance to use them as a battery energy storage system (BESS). This paper proposes a new scheme to provide necessary primary reserve from electric vehicles by using multi-agent control of each individual vehicle. The proposed scheme determines the primary reserve based on vehicle's information such as initial state of charge (SOC), the required SOC for the next trip, and the vehicle's departure time. The effectiveness of the proposed scheme is shown by the simulation study in a micro-grid with several generation units such as diesel engine generator (DEG), flywheel, fuel cell, renewable energy resources, and electric vehicles.*

Keywords: electric vehicle, primary frequency control, multi-agent control, renewable energies.

1. Introduction

Penetration level of renewable energy resources has been widely increased in many countries due to the environmental concern and fossil energy problems. Where the high penetration level of renewable resources provides new opportunities and challenges for power system operator [1]. Recently, the considerable ability of these resources to provide ancillary services, such as frequency control and spinning reserve, for power system has been proved [2].

Frequency deviation is caused by an imbalance between generation and demand. The power system operation requires to maintain frequency in acceptable range close to its nominal value, however frequency control aims to return the frequency to its nominal value by keeping the balance between total power generation and electricity consumption [3]. Practically, frequency control is divided into three control level due to their time response. Primary frequency control reacts very quickly within the first few seconds after disturbance, secondary reserve must be activated after primary reserve in 30 sec to 30 min, and finally the tertiary reserve is activated manually by re-dispatching generating units considering the economic concerns.

By controlling the demand, the more expensive reserve from conventional generating units can be avoided. The demand side can provide more reliable and less expensive primary frequency response. However, different types of demand side appliances such as refrigerators, water heaters, air conditioners, and freezers can provide primary frequency control with the minimum inconvenience to the customers. Electric vehicles (EVs) are another type of demand that can contribute to primary and secondary reserve by controlling their charging power [4]. [5] Shows that EVs can effectively improve frequency security in isolated power system.

Nowadays, there is an increasing interest in micro-grids due to their capability to provide efficient, secure, reliable, environmentally friendly, and less expensive electricity from renewable energy resources and distributed generation units [6]. The current researches in micro-grid and smart grid have a great focus on demand side management (DSM). However, the customers need to be incentivized to contribute to the DSM. In practice, the main power sources in micro-grid are small generating units with tens of kW capacities integrated to customer's side. Usually, these resources are integrated to the electricity network as a distributed generation.

Recently, many micro-grid projects have been widely investigated around the world due to the increasing importance of micro-grids in academic researches as well as practice. [7, 8, 9, and 10] report micro-grid projects in Senegal, Japan, Greece, and the United states, respectively.

As mentioned before, EVs are a good choice for providing ancillary services. The number of integrated EVs in power systems in the near future will experience a large increase, and Micro-grids provide a good infrastructure for making use of EVs for ancillary

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services provision [11]. However, the contribution of EVs to primary frequency control needs to be more comprehensively investigated.

This paper proposes a new technique for contribution of EVs to the primary frequency control. The proposed technique is based on the multi agent control. In fact, the primary reserve from EVs is calculated based on EV's information such as initial state of charge, the required state of charge for the next trip, and the temperature time. The rest of this paper is organized as follows: section 2 describes the proposed multi-agent control scheme of EVs. Electric vehicle response model is explained in section 3. The studied micro-grid and micro-grid structure is introduced in section 4. Section 5 presents the simulation scenarios and results. Finally, conclusions of the study are given in section 6.

2. Multi agent system based frequency control approach

This section describes the proposed multi-agent system based control algorithm implemented to determine primary reserve from EV. A Multi agent control scheme can be defined as a cluster or group of autonomous, interacting agents sharing a common environment. To practically realize the multi agent control schemes, smart sensor network and actuators are required [12], [13]. Multi agent based control schemes have used in a wide of variety of engineering fields such as robotics, power system automation and control. In this study, the multi agent control scheme is divided into three level as follows: a) EV agent is defined as the first multi agent level which refers to each individual EV, b) concentrate agent which is connected to all the EV agents in its area, and c) aggregator agent is connected to all concentrate agents in the micro-grid power system. There is a bidirectional communication channel between the aggregator agent and system operator (SO). The schematic diagram of the proposed multi agent system is shown in Fig.1.

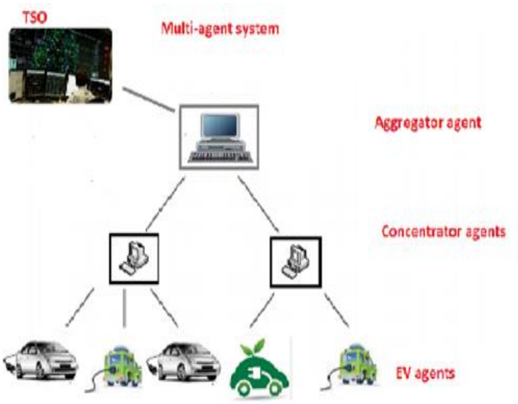

Fig.1. multi-agent EV based frequency control approach.

Each individual EV agent sends its information to the concentrator agent in its area, and the concentrator agent sends the information of EVs interested in provision of the primary reserve to the aggregator agent. The aggregator calculates the reserve available from the EVs in micro-grid. To this end, the aggregator agent needs to obtain the following information about EVs: the initial SOC, the required SOC for the next trip, their rated charging power, and departure time. Then, based on the required primary reserve announced to the aggregator agent by SO, the aggregator agent determines the share of each EV in primary frequency response.

To determine the available primary reserve for the next 15 minutes, aggregator agent divides the EVs into four groups as follows:

- Group0: EVs do not provide primary reserve due to their constraints.
- Group1: EVs provide reserve by stopping their charging.
- Group2: EVs provide reserve by stopping charging and injecting power back into grid (discharging).
- Group3: EVs (idle EVs) provide reserve by injecting power back into grid.

The above grouping is done according to the following constraints:

- $if\ \{SOC_{pot} \leq SOC_{req}\}$

  Then the vehicle is placed in group 0.

- $if\ \{p_c \neq 0 \& SOC_{pot} \geq SOC_{req} \& SOC_{inj} \leq SOC_{req}\}$

  Then the vehicle is placed in group 1.

- $if\ \{p_c \neq 0 \& SOC_{pot} \geq SOC_{req} \& SOC_{inj} \geq SOC_{req}\}$

  Then the vehicle is placed in group 2.

- If $p_c = 0 \& SOC_{inj} \geq SOC_{req}$

  Then the vehicle is placed in group 3.

Where p_c, SOC_{pot}, SOC_{inj}, SOC_{req} are the charging power, the SOC that the EV can achieve till the departure time, the SOC that the vehicle would have after discharging at the nominal power during the current time step, and the required SOC for the next trip, respectively.

According to the above grouping strategy, the primary reserve is calculated as follows:

$$p_{ev}^{1r} = \left(N_{ev}^{gr1} + 2.N_{ev}^{gr2} + N_{ev}^{gr3}\right).p_{\max} \tag{1}$$

where N_{ev}^{gr1}, N_{ev}^{gr2}, N_{ev}^{gr3}, $p_{\max}$ are the number of EVs in group1, the number of EVs ingroup2, the EV number in group3, and the maximum charging power, respectively.

In the next step, the aggregator agent sends the available reserve amount and the related bid to the SO. In this way, the aggregator agent participates in primary reserve market as the representative of all EVs. Based on competitive primary reserve market, SO announces the value of primary reserve needed to be provided by EVs to the aggregator agent. In the next step, aggregator agent broadcasts the control signal to EV agents through their concentrator agents.

The control signal includes in adjustment coefficient R and frequency dead band for EV agents in groups (1, 2) and the time response or frequency level for injecting power into grid for EV agents in groups (2, 3).

3. EV frequency response model

Based on the MERGE project of EU countries, four types of EV were identified for EU market [18]. Based on database in the aforementioned project the EV types with their battery information are represented in the next table

Table1: EV classification based on their battery type.

Classification of EV	L7e	M1	N1	N2
EV charging power [kW]	3	3	3	10
EV battery capacity [kWh]	15	72	40	120

To obtain EV frequency response model, the EV battery charger model is studied. In brief, the EV battery charger consists of an inverter to transform AC power into DC power and a buck converter to step down the voltage and increase current to an acceptable range for charging EV battery. Practically, the inverter is connected to the power system network through a small inductor (L) and resistor (R_{inv}). Power losses in the inverter is modeled by resistor (R_{loss}) [19]. The final model for EV battery charger is shown in Fig.2.

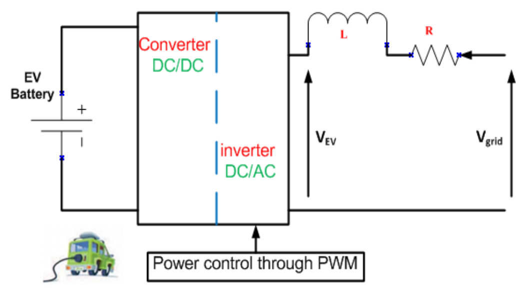

Fig2. Electric vehicle charger model.

Fig.2 shows that the inverter is controlled by pulse-width modulation (PWM) switching technique [14]. From the Fig. 3, the voltage and current equations are given as follows [15]:

$$V_{grid} = V_{ev} + V_{drop} \qquad (2)$$

$$V_{grid} = V_{ev} + L\frac{di}{dt} + R_r.i \qquad (3)$$

Where V_{grid} , V_{ev} , V_{drop} and i are the power system network voltage, EV battery voltage, voltage losses in R and L, and the current between the inverter and the grid, respectively. Also, R_r is defined by the following equation:

$$R_r = R_{loss} + R_{inv} \qquad (4)$$

The EV battery voltage can be calculated based on the DC-link voltage and modulation index of PMW M:

$$V_{ev} = \rho.\mathrm{M}.\mathrm{V}_{DC}.\sin(wt + \phi) \qquad (5)$$

Where ρ and ϕ are a constant value depending on the topology of the inverter and the angle between V_{grid} and V_{ev} , respectively. The typical values of ρ are [0.5, 1]. As shown in (3) the current between the grid and EV battery system is presented by differential equation. Consequently, the active power exchanged between the grid and EV battery would be presented by a differential equation. Therefore the frequency model of EVs is modeled using first order lag function with EV time constant T_{ev} . The EV time constant can be calculated easily from equation (2) as follows:

$$T_{ev} = \frac{L}{R_r} \qquad (6)$$

Depending on the above discussion, in power system frequency studies EV would be modeled by a first order transfer function:

$$\frac{1}{1 + sT_{ev}} \qquad (7)$$

T_{ev} is considered 0.05 second in this paper. However, the EV time constant can be used as a variable number between 35ms and 100ms [16, 17].

The aggregate model of all EVs available in the system can be modeled as shown in Fig. 3. In practice, primary frequency control consists of adjusted frequency droop coefficient R which depends on primary reserve from EV and frequency dead-band with upper and lower power limits. Dynamic function block of primary frequency control of EV is shown in Fig 3.

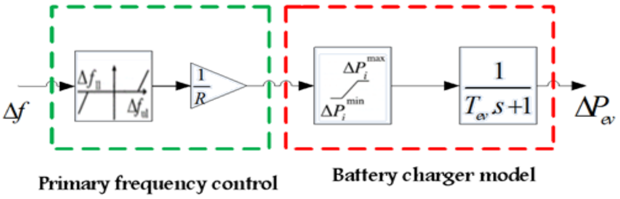

Fig.3. dynamic model of EV for primary frequency control

Table2. EV parameters.

EV parameters	Symbol	value
EV response time in [sec]	T_{ev}	0.005
Adjusted coefficient	R	0.05
Dead-band	DB	|0.00002|
Maximum reserve in [p.u]	ΔP^{up}	0.13
Minimum reserve in [p.u]	ΔP^{down}	-0.13

4. The studied micro-grid

The studied micro-grid system consists of generating units, loads and EVs as shown in Fig.4. Various generating units like wind turbine generator (WTG), photovoltaic (PV), flywheel energy storage system (FESS), DEG and fuel cell (FC) are implemented in this micro-grid. Every individual generating unit is modeled using a first order transfer function suitable for low frequency domain study [20]. The transfer functions of generating units under study are adopted from [20].

The transfer function of the WTG is represented by a first-order lag function as:

$$G_{wtg}(s) = \frac{K_{wtg}}{T_{wtg}.s+1} \qquad (8)$$

Where K_{wtg}, T_{wtg}, s are the wind turbine generating unit gain, response time of wind turbine to frequency deviation, and Laplace operator, respectively.

A transfer function is used to represent PV in this study:

$$G_{pv}(s) = \frac{K_{pv}}{T_{pv}.s+1} \qquad (9)$$

Where K_{pv} and T_{pv} are the photovoltaic system gain and the response time of photovoltaic unit, respectively.

DEG is modeled by a transfer function as follows:

$$G_{deg}(s) = \frac{K_{deg}}{T_{deg}.s+1} \qquad (10)$$

Where K_{deg}, T_{deg}, s are the diesel engine generator constant, the time response of diesel generator unit, and Laplace operator, respectively.

The transfer function of FC is considered as a first order lag function:

$$G_{fc}(s) = \frac{K_{fc}}{T_{fc}.s+1} \qquad (11)$$

Where K_{fc}, T_{fc} are the fuel cell constant value and the time response of fuel cells unit, respectively.

The first order lag transfer function of FESS for frequency studies is represented as follows:

$$G_{fl}(s) = \frac{K_{fl}}{T_{fl}.s+1} \qquad (12)$$

Where K_{fl}, T_{fl}, s are the flywheel gain, the response time of flywheel, and the Laplace operator, respectively.

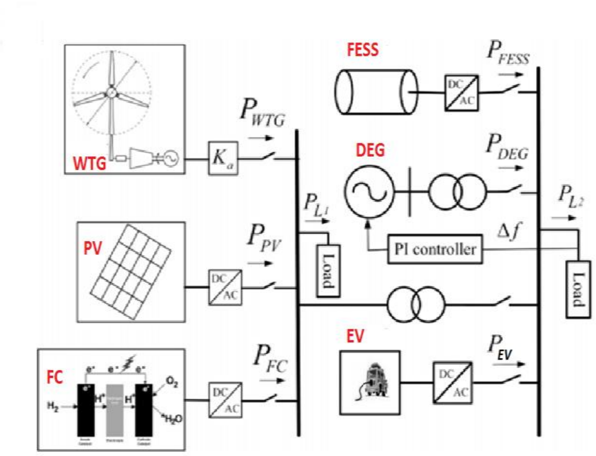

Fig.4. micro-grid topology

5. Simulation study and results

A multi agent electric vehicle control scheme is used to determine the primary reserve from EVs in the aforementioned micro-gird. After determining reserve amount of all EVs in the micro grid for specific time, simulation study is carried out in Matlab/Simulink program 2014b and a computer with core i7 Intel CPU and 12 GB RAM.

This study discusses the EVs' impact on primary frequency response in the studied micro-grid when a single disturbance is occurred. The single disturbance is defined as 15% increasing in demand. This case study is divided into two scenarios: the first scenario investigates the effect EV reserve on the frequency stability after a disturbance event, also the effect of EV on diesel engine generated power. The second scenario studies the difference between primary frequency control of EV with and without droop coefficient.

The parameters of the micro-grid model used for the simulation studies are adopted from [20]:

$K_{WTG} = K_{FESS} = 1$, $D = 0.015$ pu/Hz, $2H = 0.1667$ pu s,
$T_{FESS} = 0.1$ s, $T_{FC} = 0.26$ s, $T_{WTG} = 1.5$ s, $T_g = 0.08$ s,
$T_t = 0.4$ s, $T_{I/C} = 0.004$ s, $T_{IN} = 0.04$ s, $R = 3$ Hz/pu.

Power generation limits, ramp up rate (RUR), and ramp down rate (RDR) of the power sources are given in table3:

Table 3. Output power and constraint rats of all generation unit in the MG [21].

generators	**Max power [p.u]**	**Min power [p.u]**	**RUR [p.u/sec]**	**RDR [p.u/sec]**
FESS	0.12	-0.12	0.04	-0.04
FC	0.47	0	1	-1
DGE	0.44	0	0.5	0.5
EV	0.13	-0.13	0.05	0.05

Fig. 6 shows that the frequency decline starts after disturbance instantly. The curve with doted black line shows the frequency decline without EV participation, and the frequency nadir in this scenario is dropped below 59 Hz. It is worth noting that, in the studied micro-grid, a frequency deviation more than 0.8 Hz may lead to load shedding. The blue line curve in Fig.6 represents the frequency behavior when EVs contribute to frequency event by stopping their charging. It is clear that the frequency response is enhanced and the frequency nadir is above the load shedding frequency threshold (59.2Hz). Also, this figure shows frequency decline when EVs injected their power back into the grid and controlled their power by a fixed droop coefficient R.

It can be understood from Fig. 7 that the required response from DEG is reduced when EVs contribute to frequency response. The maximum change of output power of diesel engine without EV is 0.025 p.u which is reduced to 0.014 p.u when EVs participate in frequency response.

Two different control strategy of EV participation in frequency response is compared here. In one of the control strategies, which has been proposed in [17], EVs inject their maximum power to the grid if the frequency falls below 59.7 Hz. In the second strategy which is suggested in this paper, a droop based method is used for participation of EVs in primary frequency response. The value of droop is determined by aggregator agent based on the aforementioned multi-agent scheme. Fig.8 shows frequency response in studied micro-grid when all EVs are controlled with/without droop.

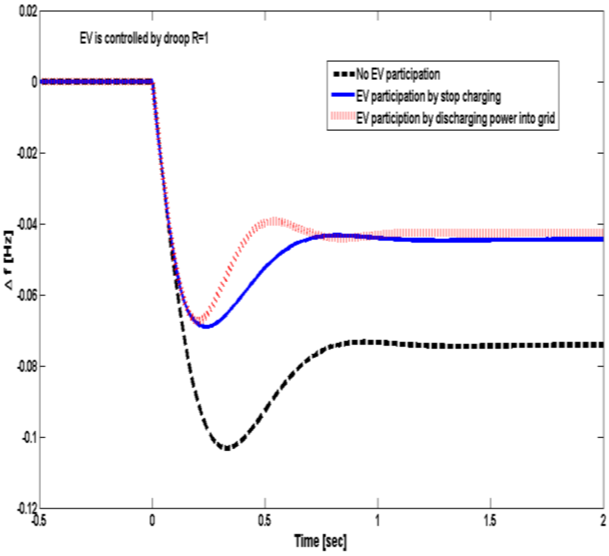

Fig.6. frequency response in the MG w/o EV participation in scenario1.1.

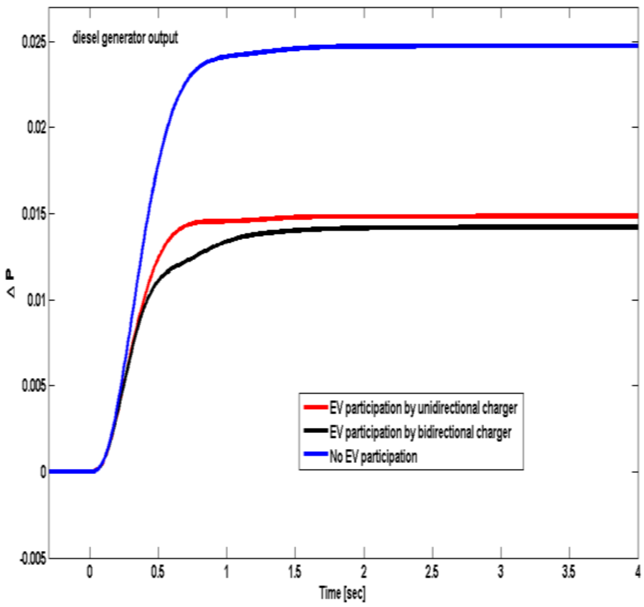

Fig.7. diesel engine power response to the frequency deviation.

The worse frequency response is happened when EVs are controlled without fixed droop coefficient due to over response of EV to frequency deviation. In this case, the frequency is risen above 60 Hz and in more severe cases it may trigger the over frequency protection relays. However, it is evident from Fig. 8 that when suitable value of droop is determined using the proposed multi-agent scheme, not only the minimum frequency is maintained above the permissible limit but also over frequency condition is prevented. As a conclusion of this scenario, the EVs response must be controlled by fixed droop to insure suitable response from EVs to frequency events.

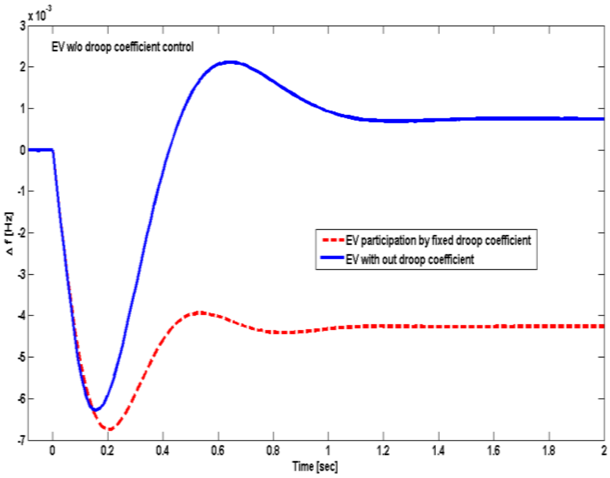

Fig.8. primary response frequency of EVs w/o droop controller.

6. Conclusion

In this paper, primary frequency control in micro-grid system which is one of the important issues was investigated. A multi-agent control scheme for participation of EVs in primary frequency control of an AC micro-grid has been proposed. The proposed multi-agent based control scheme consists of three agent levels. For the proper operation of the proposed scheme, some information, such as the initial SOC and departure are required. Simulation studies proved the effectiveness of the proposed strategy in primary frequency control. It has been shown that using the proposed control scheme, not only the frequency nadir is maintained above the minimum allowed value but also the steady state frequency will be brought back to the acceptable level. In addition, due to the fast response of EVs, the other generating units such as DEG will be less stressed for providing primary frequency response. Furthermore, it has been illustrated that the proposed droop based method is superior to another control method which had been newly proposed in the literature.

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